An experimental investigation into innovative pavements for city logistics

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Abstract

Crumb rubber modified asphalt mixtures (CRM, dry process) involve the blending of crumb rubber (usually 1%–3% by weight of the total mixture, sizes 2.0 mm/6.3 mm) with hot aggregates prior to mixing with asphalt binder. It may cost more than conventional asphalt concretes.

On the contrary, the wet process implies incorporating crumb rubber into asphalt binder prior to mixing with aggregates (usually about 1% by weight of the total mixture, 18–25% by weight of bitumen, rubber sizes below about 0.18–0.42mm) and has a wide and quite sound theory and procedure system behind it. Crumb rubber modified asphalt pavements may cost 1.5 to 2 times as much as conventional asphalt concrete.

Importantly, although the dry process has a number of technical issues (including lack of standards, and uncertain performance), it has the potential to recycle more crumb rubber compared with the wet process and its mechanical properties (modulus and mechanical impedance) appear to have the potential for constructing innovative urban and rural infrastructures and for greening European city terminals.

In light of the above, the goals of this study were the following: a) designing and testing innovative bituminous mixtures containing high percentages of crumb rubber (dry process); b) designing and testing innovative pavements in which the pressures caused by vehicles and/or motorcycles and/or pedestrians are converted into energy. Several mixes were designed and produced. Based on the results obtained, several options emerged as a possible solution for urban and rural roads, aiming at a better management of flow of goods and transport activities in urban areas while considering lower environmental impacts.

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Although studies are in progress, results are quite encouraging and can benefit both researchers and practitioners.
Keywords: crumb rubber, dry process, urban transport, pavement, freight terminal, city logistics, urban transport centre.

1 Introduction

Crumb rubber (CR) can be used to modify asphalt mixtures. CR is made of tyres or vulcanized rubber from different devices and tools. For example, the components of fire extinguishers include metallic parts (discharge valve assembly, squeeze grip release lever locking pin d-yoke ring, carrying handle, band horn clip, insulated handle, and horn), but also rubber parts (hose, etc.).

Hose material is usually ethylene propylene diene monomer (EPDM) rubber. It is a type of synthetic rubber, and it is an elastomer characterized by a wide range of applications. The M refers to its classification in ASTM standard D-1418, where the M class includes rubbers having a saturated chain of the poly-methylene type.

The ethylene content is around 45% to 85%. The main properties of EPDM are its heat, ozone, and weather resistance. Density can be compounded from 0.90 to more than 2 g/cm^3.

Tyres are basically formed by combining natural and synthetic rubber and carbon black [1].

CR is typically referenced by its size together with basic compositions such as natural and synthetic rubber, steel, fibre and carbon black. In tyre production, the vulcanization process plays a fundamental role and enhances its elasticity and strength properties.

There are *two main methods* for processing scrap tyres and other waste rubbers, namely ambient granulating (crackermill process) and cryogenic grinding [1].

Two different processing methods are usually used to combine rubber, aggregates and asphalt binder: wet and dry process.

In the wet process [2, 3], fine rubber is blended with hot bitumen to produce a rubberised bitumen binder. The wet process implies incorporating crumb rubber into an asphalt binder prior to mixing with aggregates (usually about 1% by weight of the total mixture, 18%–25% by weight of bitumen, rubber sizes below about 0.18–0.42mm) and has a wide and quite sound theory and procedure system behind. Crumb rubber modified asphalt pavements may cost 1.5 to 2 times as much as conventional asphalt concrete.

Crumb rubber modified asphalt mixtures (CRM, dry process) involve the blending of crumb rubber (usually 1%–3% by weight of the total mixture, sizes 2.0 mm/6.3 mm, see [4–6]) with hot aggregates prior to mixing with an asphalt binder. It may cost more than conventional asphalt concretes.

Usually a proportion of the mix aggregate is substituted with coarse rubber, thereby causing the rubber to function essentially as an elastic aggregate within the mixture [1].

In the dry process, composition (rubber gradation, rubber content, aggregate gradation, bitumen type and quantity) and process (reaction time between asphalt binder and rubber particles, etc.) affect mixture properties.

Rubber–bitumen interaction is supposed to be based on the following phenomena: rubber absorbs the maltenes fraction (which has low molecular weight) and leaves the residual bitumen containing a higher portion of asphaltenes (of high molecular weight) which increases its viscosity (see [1, 7–9]) and causes the increase of the dimensions of the rubber network (swelling).

By limiting the above reaction time and using a coarse granulated rubber with a low surface area, the rubber particles may be able to retain their physical shape and rigidity. The curing period seems to be necessary so as to provide sufficient time for the rubber to swell and partially dissolve in the bitumen prior to compaction [1]. Better performance can be achieved by providing a long interaction time between the rubber and bitumen but not in excess of 2 hours.

For CRM mixture performance, the main advantages and disadvantages may include (see [1, 3, 10, 11]): i) the ability to break up ice; ii) a better skid resistance during icy conditions; iii) the enhancement of elastic recovery properties under repeated loading; iv) the enhancement of the mixture's resistance against fatigue cracking; v) the improvement of crack reflection control; vi) the improvement of fatigue life; vii) the improvement of reflective cracking resistance if a minimum rubber content is added to the paving mix (probably between 1 and 2 percent by weight of aggregate); viii) the decrease of the resilient modulus; ix) the reduction of the resistance to permanent deformation; x) the reduction of Marshall stability values.

Lopez-Moro *et al.* [12] carried out a microscopy study of the modification of bitumen with crumb rubber, using the dry process. They observed: i) the transfer of maltenes to the rubber and carbon black to the bitumen, causing the absorption of the lighter-oil fractions of bitumen; ii) that the modification increased the stiffness of the bitumen, resulting in an improvement in the binder's resistance to rutting. Feiteira-Dias *et al.* [13] evaluated the mechanical response of two gap-graded asphalt rubber mixtures manufactured by the dry process and compared results; a) with that of a similar gap-graded mixture without rubber granulate; b) with analogous asphalt rubber mixes produced elsewhere by the wet process. They found that the mechanical performance of the dry mixes was better than that measured for the reference blend and was at the same level of performance as the wet mixes.

The above advantages and disadvantages might suggest the possibility to use these materials in given applications (inverted pavement structures; softer asphalt concretes with lower modulus and higher allowable strain limit and lower noise, etc., see [14–18]). Static possible applications could refer also to equipment and automobile parking (porous asphalt on low modulus hot mix asphalts (HMA)), intermodal yard (traditional HMA on low modulus HMA), gate facilities and secondary gate facilities (traditional HMA on low modulus HMA), wheeled and grounded container storage (in association with rolled cement concretes), expansion areas (traditional HMA on low modulus HMA), wharf areas (in association with rolled cement concretes), historical locations (see [19–21]).

Another opportunity refers to the use of sensors embedded into the pavement layers in order to improve pavement management systems, safety and security in urban and rural conditions and in intermodal freight connectors.

Continuous monitoring of the pavement structural/surface condition (using self-powered sensors) with periodic high-speed inspections of the surface can enable us to optimize cost, timing and intensity of maintenance and rehabilitation treatments. For the self-powered systems for data gathering (smarter maintenance and rehabilitation), an energy harvesting stick can generate the power, with additional, advanced applications (gathering and transmission of accident, speed, weather, pollution data; energy supply for road safety systems; gathering and transmission of administrative data, etc.). The self-powered systems for data gathering have a technology concept formulated readiness level (see [22–25]).

The monitoring effect on agency, user and externality costs involves the consideration of the reliability of a pavement (probability that a pavement section designed using the process will perform satisfactorily for the anticipated traffic and environmental conditions for the design period). The following factors may impact the design reliability: materials; subgrade; traffic prediction accuracy; construction methods; and environmental uncertainties.

The following main issues still need to be addressed for smarter maintenance and rehabilitation of multimodal transportation infrastructures: i) survey-based asset management systems do not necessarily allow a timely and productive management of the infrastructure. This issue calls for further research; ii) a better amalgamation between information communication technology (ICT) and infrastructure management should be pursued. Indeed, they both can address the overall aim of smarter transport infrastructures, by affecting users' costs (information, time), agency costs (work zones, long-life), and externality costs (carbon footprint of maintenance and rehabilitation occurrences); iii) when low-volume roads, pedestrian facilities, bicycle paths, low emission zones are taken into consideration, several energy harvesting systems, based on pressure-voltage transformation on a fixed path, may fail to achieve the best solution and other systems can achieve viable results. These issues call for further research and investigation.

The recycling of reclaimed asphalt pavement (RAP) interacts with the above issues and opportunities. Medium- to very high-content of reclaimed asphalt pavement use was reported by a number of authors [26–35].

In contrast, different strategies of blending and use of RAP (e.g., blends with recycled concrete aggregate, with rice husk ash, with lateritic soil, with asphalt shingle, use in granular bases and subbases) were proposed by others [36–41].

Importantly, based on mechanical properties and layer design (modulus, thickness, Poisson coefficient), life cycle cost analysis can be helpful in assessing the present value of each solution and then its real competitiveness [42].

Finally, it may be observed that last-mile and long distance logistics [43, 44], microsimulation in the city terminal [45], and urban regeneration aspects [46] are other relevant topics not discussed in the following.

2 Objectives

Although the dry process has a number of technical issues (including lack of standards, and uncertain performance), it has the potential to recycle more crumb rubber compared to the wet process and its mechanical properties (modulus, mechanical impedance) appear to have the potential for constructing innovative urban and rural infrastructures and for greening European freight terminals.

Consequently, the following objectives were pursued: a) designing and testing innovative bituminous mixtures containing waste rubber; b) designing and testing innovative pavements in which the pressures caused by vehicles and/or motorcycles and/or pedestrians are converted into energy.

3 Experiments and analyses

Figure 1 summarises the overall experimental plan, in terms of crumb rubber characteristics and mixes produced. Figures 2–3 illustrate the results obtained.

Figure 2 shows how the Marshall stability (MS, kN, y-axis) varies as a function of the air voids content (AV, %, x-axis), for crumb rubber modified asphalt mixtures (Y CR), asphalt mixtures without crumb rubber (NO CR), and all the mixtures (ALL), under the given hypotheses.

Note that: i) only two gradations were considered (type A, for dense-graded friction courses and type B, for porous asphalt concretes); ii) the same percentage of asphalt binder was considered (nominal value of 5.5% by weight of mix); iii) CRM asphalt mixtures contained the same percentage of CR (10%, which substituted the corresponding mineral aggregate portion); iv) the same type of asphalt binder was used (penetration grade: 50–70).

Figure 3 illustrates how the Marshall quotient (MQ, kN/mm) varies as a function of AV, for the same mixes.

Results demonstrate that the addition of CR to the mixtures implies a reduction of Marshall stability and quotient. It appears noteworthy to highlight that the asphalt binder film thickness depends on particle specific gravity which changes when aggregate specific gravity changes [47–49]. Consequently, the above comparison, which entails the use of the same percentage of bitumen, appears to bring us to conclusions which are consistent with the ones reported in [1, 8].

As a part of the overall experimental plan (projects CADI-PIA Gomme, Cadi dei Fratelli Milasi Srl, Reggio Calabria, Italy and project SUS PAV), mixes with different percentages of bitumen and the same asphalt film thickness are under production. Similarly, experiments involving the use of reclaimed asphalt pavement, sensors and piezoelectric energy systems are currently going on.

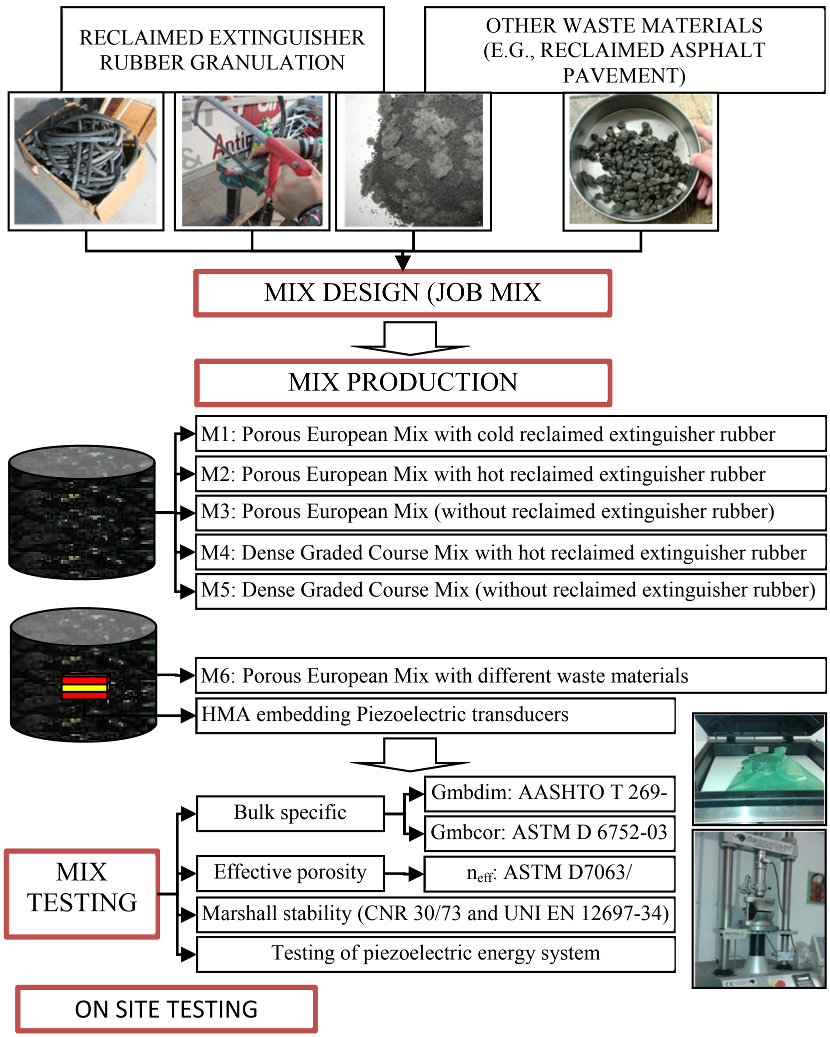

Figure 1: Design of experiments.

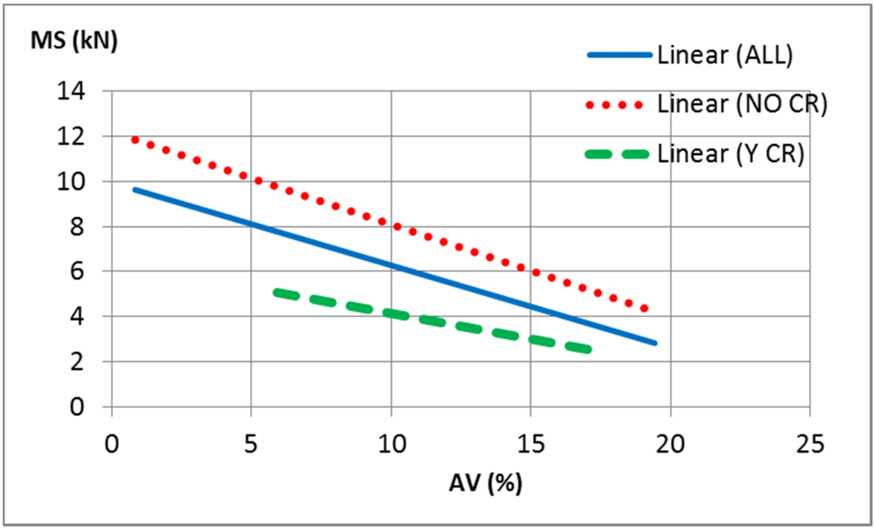

Figure 2: Marshall stability as a function of air voids content.

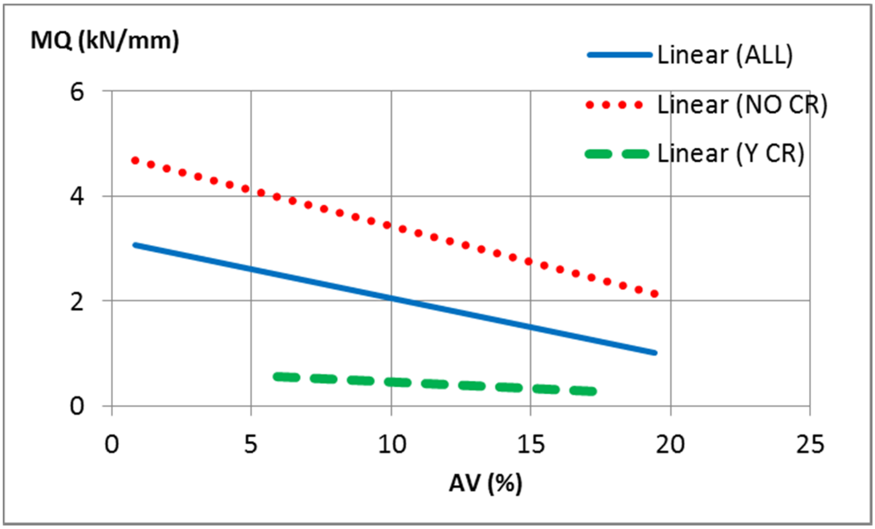

Figure 3: Marshall quotient as a function of air voids content.

4 Conclusions

Although the dry process has a number of technical issues (including lack of standards, and uncertain performance), it has the potential to recycle more crumb rubber compared to the wet process and its mechanical properties (modulus, mechanical impedance) appear to have the potential for constructing innovative urban and rural infrastructures and for greening European freight terminals.

In light of the above, the goals of this study were the following: a) designing and testing innovative bituminous mixtures containing high percentages of crumb rubber (dry process); b) designing and testing innovative pavements in which the pressures caused by vehicles and/or motorcycles and/or pedestrians are converted into energy. Several mixes were designed and produced. Based on the results obtained, several options emerged as a possible solution for urban roads, rural roads, container terminals, and freight terminals. Aggregate gradation, bitumen (percentage and quality) and air voids content resulted as the possible keys to success in designing a CRM mixture. Higher bitumen content is supposed to be needed for the CRM mixtures compared to the conventional open-graded and dense-graded mixtures, for the same aggregate type.

Although studies are in progress, results are quite encouraging and can benefit both researchers and practitioners.

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